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A STUDY OF MILLIMETER AND SUBMILLIMETER WAVE ATTENUATION AND DISPERSION IN THE EARTH'S ATMOSPHERE

M. Greenebaum, et al

Riverside Research Institute

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A summary is presented of new calculations of atmospheric absorption line parameters and of a slant-path absorption model (SLAM) intended for use in the millimeter and submillimeter wave spectral regions. Results of a literature survey concerning altitude-dependent attenuation and dispersion in this spectral region, as well as weather-dependent scattering and fading strengths, are also summarized. Recommendations are given for

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A list of 318 absorption lines of the molecular oxygen isotopes of principal concern in atmospheric transmission below 300 cm^{-1} is included, together with their integrated strengths at 296K, line widths, lower-state energies, and identifying quantum numbers, in the format of the AFCRL Atmospheric Absorption Line Parameters Compilation. Reference is made to a series of Technical Reports which give complete documentation of the calculations leading to these values and to similar calculations for carbon monoxide, as well as of a detailed description of the SLAM program.

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A STUDY OF MILLIMETER AND SUBMILLIMETER WAVE ATTENUATION AND DISPERSION IN THE EARTH'S ATMOSPHERE

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AUTHORIZATION

The research described in this report was performed by M. Greenebaum and D. Koppel, with the assistance of S. Rosenberg. This report was compiled and edited by M. Greenebaum and M. King.

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Research Director

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I. INTRODUCTION AND SUMMARY

A. PROGRAM OBJECTIVES

The millimeter and submillimeter wave region has been of increasing interest to both the research and technology communities over the past twenty years. The principal difficulties preventing more extensive use of this sub-terahertz spectral region are connected with the atmospheric propagation characteristics. In much of the region, the atmosphere is essentially opaque at low altitudes, but precise measures of the degree of opacity as a function of altitude have not been readily available. Recent increases in the understanding of the relevant molecular spectroscopy at both the theoretical and experimental levels, together with the current development of more powerful sub-terahertz sources, led RRI to propose the study of millimeter wave propagation in the atmosphere which is the subject of this report. The specific objectives of this study were as follows:

To review the experimental and theoretical data now available concerning atmospheric propagation of millimeter and submillimeter waves and use this data to predict the altitude-dependent transfer characteristics of principal interest for ARPA-related systems studies. These were to be "state-of-the-art" predictions based on a comprehensive literature search emphasizing attenuation and dispersion, but also addressing questions of weather-dependent scattering and expected fading strengths. Inadequacies in the present data base were to be exposed by determining the degree of uncertainty resulting in the predicted transfer characteristics. RRI was to recommend

data-gathering or verification experiments which might be required to eliminate the inadequacies in this data base. Finally, RRI was to develop a computer model of the atmosphere which would be of general utility wherever the sea-level attenuation is 3dB/km or less.

B. SUMMARY OF RESULTS

From the study of the journal and report literature on altitude-dependent transfer characteristics in the millimeter and submillimeter region, it became evident that the only atmospheric absorbers generally considered were water vapor, oxygen (microwave region only), and--occasionally--ozone. On the other hand, from recent studies of the stratospheric emission from the atmosphere, it was clear that other species, especially oxygen, were important in the submillimeter region. Therefore, a state-of-the-art computer model was developed[1] which would predict the transfer characteristics using as input the absorption line parameters in "AFCRL format" for any species of interest, and an appropriate set of line parameters for oxygen[2] and carbon monoxide[3] was developed, supplementing the already-existing data[4] on water and ozone. (Additional species of importance, such as NO_2, will be added in a follow-on study.[5]) These new line parameter calculations have also been made available to AFCRL[6] for incorporation into their master list of line parameters[4] for DoD-wide and general use. The dominant uncertainties in the absorption calculations were determined to be tied up with the oxygen line widths and their pressure dependence[2] and with the still-unresolved issue of the correct line-shape to use for the water absorptions.[1] The computer model (SLAM) is a high-resolution, slant-path absorption model used to generate predictions, at any altitude below 40 km, of the local attenuation (dB/km) as well as the total attenuation (dB) from that altitude out to space and down to sea level.[1] Extensions of the model to dispersion calculations

is possible under algorithms which have recently been worked out.

The literature survey revealed that the dispersion and attenuation in the 60 GHz oxygen complex have been under active study at OT/ITS,[7] and that better line widths for oxygen are becoming available as a result.[2] Scattering by dry aerosols and by various water cloud models in the submillimeter region has been studied recently,[8] so that it did not prove necessary to spend much time on the scattering problem. The key uncertainty remaining is scattering at high altitudes, especially by cirrus clouds, whose particles are irregularly shaped and faceted, and whose complex index of refraction at temperatures characteristic of such clouds is imprecisely known.[8] (RRI has proposed to study the complex index of refraction at these temperatures.[9])

Dispersion and fading has been studied most extensively by the Russians,[10-13] and (only in the millimeter-wave region) by workers in the U. S.,[14] England,[15] and Germany.[16] The most recent Russian work was studied by abstract only, since the conference proceedings proved to be unavailable.[17] Sufficient theoretical understanding of the dispersion/fading relationship exists for it to be possible to extend the SLAM program to make detailed predictions in any desired frequency range, should the r[illegible]ise. Such extensions are not provided for under the [illegible]t contract or its immediate follow-on.[5]

C. ORGANIZATION OF THIS REPORT

Sections II through IV summarize the computer calculations performed during the period 1 March through 15 August 1975, in support of this Contract Modification. Much more detail will be found in a series of Technical Reports[1-3] which include complete program documentation on the subjects covered. Section II describes the nature of the calculation of millimeter and submillimeter wave absorption line parameters for the

molecular oxygen isotopes, $^{16}O_2$, $^{16}O^{18}O$, and $^{18}O_2$ (with $^{16}O^{17}O$ to be the subject of a separate Technical Report[18]).[2] Sec. III describes the status of the slant-path absorption model (SLAM) development as of 15 August.[1] Section IV briefly describes the calculations performed of the absorption line parameters of several isotopes of carbon monoxide, of which only $^{12}C^{16}O$ turns out to be significant.[3] The preliminary calculations on NO and on $^{16}O^{17}O$ are also discussed, as are several miscellaneous computations which will be of use in related problems.

Section V summarizes the results of the RRI survey of the atmospheric propagation literature, atmospheric models, and trace-species spectroscopy in the millimeter and submillimeter wave regions. Section VI contains our recommendations for experimental studies and data-gathering needed to improve the data base for computations of altitude-dependent transfer characteristics and their degree of variability.

II. CALCULATION OF MILLIMETER AND SUBMILLIMETER ABSORPTION LINE PARAMETERS FOR THE MOLECULAR OXYGEN ISOTOPES: $^{16}O_2$, $^{16}O^{18}O$, AND $^{18}O_2$

One of the principal objectives of the RRI efforts on atmospheric propagation in the millimeter-through-submillimeter wave region has been to develop detailed predictions of the molecular attenuation as a function of frequency and altitude. To aid in this study, a computer tape was obtained from AFCRL in April 1975 which contained the AFCRL Atmospheric Absorption Line Parameters Compilation,[4] converted to the 9-track format compatible with RRI's XDS Sigma 9 computer, and listed from the beginning to 585.5 cm^{-1} (the first 8095 absorption lines). This computer tape was to be used as input for the SLAM program described in Section III and in Tech. Report T-2/306-3-14.[1] However, study of the printout of the first several thousand lines revealed that all of the important oxygen absorption lines in the submillimeter region (starting at 12.292 cm^{-1})[19] were absent, as were all of the carbon monoxide (CO) and nitrous oxide (N_2O) pure rotation lines. In addition, the microwave oxygen absorption lines had incorrect line-widths. This meant that the AFCRL compilation could be used for H_2O (all isotopes) and $^{16}O_3$ (ozone) in the submillimeter region, but that absorptions due to all other species (oxygen being most important[20]) would have to be added.

From preliminary computations of the line positions and strengths for molecular oxygen, it was obvious that much more work would be required: the absorption frequencies quoted in the literature[19-22] for the submillimeter spectrum were discrepant by more than 0.1 cm^{-1}; transition matrix elements were

available only for the first 24 lines (to 96.81 cm^{-1}); line-width estimates[19,22] were 50 percent discrepant.

Based on the 1955 work of Tinkham and Strandberg[21] (as corrected by Gebbie, et al.[19] in 1969), transition matrix elements were generated for 15 more $^{16}O_2$ lines with the aid of a HP-35 calculator. Line strengths remained high even at 153.87 cm^{-1}, consistent with observations of O_2 lines in emission out to 200 cm^{-1} in the stratosphere.[22] However, the observed lines appear at frequencies[22] which are in significant discrepancy with Gebbie's values[19,20] and no line-strength computations had been published for the high-frequency lines. It was decided to re-do the Tinkham-Strandberg calculations ab initio, therefore, based on the latest estimates of the oxygen molecular parameters (B_0, B_1, B_2, λ_0, λ_1, μ_0, and μ_1).[23-28] The necessary calculations were performed, a set of APL computer programs was written for the XDS Sigma 9 computer, and these programs were executed to generate a reliable set of line parameters for molecular oxygen isotopes $^{16}O_2$, $^{16}O^{18}O$, and $^{18}O_2$ (all of which have nuclear spin $I = 0$). These computations are fully documented in Tech. Report T-1/306-3-14.[2] Table I gives the relative isotopic abundances of the various oxygen isotopes from which it is evident that ignoring $^{16}O^{17}O$ (which has a more complicated spectrum owing to the hyperfine structure induced by the spin $I = 5/2$ of the ^{17}O atom) will not hurt too much in a "first cut" study of the atmospheric transfer characteristics. Nevertheless, $^{16}O^{17}O$ (as well as the Zeeman effect in $^{16}O^{16}O$, important at high altitudes[7]) will ultimately be included in the line parameter compilation,[18] although it is not treated here or in Ref. 2.

Table II, taken from Appendix G of Ref. 2, is a file listing of the absorption line parameters for the three molecular isotopes considered whose line strengths exceed $3.7 \cdot 10^{-30}$ cm^{-1} per (molecule cm^{-2}), based on the molecular parameters of Steinbach

Table I: Relative Abundances of the Isotopes of O_2

Isotopic Species	Relative Abundance[a]
$^{16}O^{16}O$	0.99519
$^{16}O^{18}O$	$4.07 \cdot 10^{-3}$
$^{16}O^{17}O$	$7.38 \cdot 10^{-4}$
$^{18}O^{18}O$	$4.16 \cdot 10^{-6}$
$^{17}O^{18}O$	$1.51 \cdot 10^{-6}$
$^{17}O^{17}O$	$1.37 \cdot 10^{-7}$

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[a] Based upon the following isotopic abundances of atomic oxygen: ^{16}O: 99.759%, ^{17}O: 0.037%, ^{18}O: 0.204%

Reference: Handbook of Chemistry and Physics, 52nd Edition, 1971-1972, Chemical Rubber Co., Cleveland, Ohio.

Table I

OXYGENEXIST ABSORPTION LINE PARAMETERS FOR MOLECULAR OXYGEN ISOTOPES (AFCRL FORMAT)

ALL LINES OF 016-016, 016-018, AND 018-018 WITH V = 0 OR 1
AND WHOSE STRENGTHS EXCEED 3.7E-30 INV CM PER MOLECULE PER CM SQ
AT 296K. LINEWIDTHS INTERPOLATED FROM KRUPENIE'S COMPILATION,
B0, B1, B2, ETC., FROM REF. 7 FOR V = 0, FROM REF. 5 FOR V = 1.

	FREQ	STRENGTH	WIDTH	E''	V'	J'	K'	V''	J''	K''	ID	DATE	ISO	MO
1	1.64953	4.62E-30	.032	2460.774	0	41	41	0	40	41	41-	75	66	7
2	1.66655	1.38E-29	.032	2230.425	0	39	39	0	38	39	39-	75	66	7
3	1.68362	3.87E-29	.032	2011.215	0	37	37	0	36	37	37-	75	66	7
4	1.70076	1.03E-28	.032	1803.180	0	35	35	0	34	35	35-	75	66	7
5	1.71796	2.58E-28	.032	1606.353	0	33	33	0	32	33	33-	75	66	7
6	1.73524	6.09E-28	.032	1420.767	0	31	31	0	30	31	31-	75	66	7
7	1.75262	1.36E-27	.032	1246.452	0	29	29	0	28	29	29-	75	66	7
8	1.76431	3.73E-30	.032	1178.121	0	29	29	0	28	29	29-	75	68	7
9	1.77012	2.85E-27	.032	1083.436	0	27	27	0	26	27	27-	75	66	7
10	1.77256	5.33E-30	.032	1099.777	0	28	28	0	27	28	28-	75	65	7
11	1.78084	7.49E-30	.032	1024.107	0	27	27	0	26	27	27-	75	68	7
12	1.78776	5.63E-27	.032	931.745	0	25	25	0	24	25	25-	75	66	7
13	1.78914	1.04E-29	.032	951.113	0	26	26	0	25	26	26-	75	68	7
14	1.79748	1.42E-29	.032	880.799	0	25	25	0	24	25	25-	75	68	7
15	1.79998	5.57E-30	.038	2339.133	1	23	23	1	22	23	23-	75	66	7
16	1.80558	1.05E-26	.038	791.405	0	23	23	0	22	23	23-	75	66	7
17	1.80586	1.91E-29	.035	813.167	0	24	24	0	23	24	24-	75	68	7
18	1.81428	2.54E-29	.038	748.219	0	23	23	0	22	23	23-	75	68	7
19	1.81923	9.67E-30	.035	2211.583	1	21	21	1	20	21	21-	75	66	7
20	1.82275	3.32E-29	.037	685.959	0	22	22	0	21	22	22-	75	68	7
21	1.82363	1.83E-26	.035	662.437	0	21	21	0	20	21	21-	75	66	7
22	1.83127	4.28E-29	.035	626.388	0	21	21	0	20	21	21-	75	68	7
23	1.83877	1.58E-29	.037	2095.301	1	19	19	1	18	19	19-	75	66	7
24	1.83986	5.43E-29	.036	569.509	0	20	20	0	19	20	20-	75	68	7
25	1.84199	3.00E-26	.037	544.863	0	19	19	0	18	19	19-	75	66	7
26	1.84852	6.78E-29	.037	515.324	0	19	19	0	18	19	19-	75	68	7
27	1.85727	8.34E-29	.038	463.835	0	18	18	0	17	18	18-	75	68	7
28	1.85869	2.41E-29	.038	1990.305	1	17	17	1	16	17	17-	75	66	7
29	1.86075	4.60E-26	.038	438.702	0	17	17	0	16	17	17-	75	66	7
30	1.86611	1.01E-28	.038	415.043	0	17	17	0	16	17	17-	75	68	7
31	1.87509	1.20E-28	.038	368.952	0	16	16	0	15	16	16-	75	68	7
32	1.87679	2.74E-26	.045	2.084	0	1	1	0	2	1	1+	75	66	7
33	1.87915	3.43E-29	.038	1896.613	1	15	15	1	14	15	15-	75	66	7
34	1.88008	6.58E-26	.038	343.970	0	15	15	0	14	15	15-	75	66	7
35	1.88420	1.41E-28	.038	325.562	0	15	15	0	14	15	15-	75	68	7
36	1.88985	1.42E-29	.045	1558.465	1	1	1	1	2	1	1+	75	66	7
37	1.89204	5.40E-29	.045	2.633	0	1	1	0	2	1	1+	75	68	7
38	1.89350	1.62E-28	.039	284.875	0	14	14	0	13	14	14-	75	68	7
39	1.90026	8.77E-26	.039	260.083	0	13	13	0	12	13	13-	75	66	7
40	1.90041	4.56E-29	.039	1814.239	1	13	13	1	12	13	13-	75	66	/
41	1.90302	1.83E-28	.039	246.893	0	13	13	0	12	13	13-	75	68	7
42	1.91282	2.03E-28	.040	211.617	0	12	12	0	11	12	12-	75	68	7
43	1.92175	1.08E-25	.041	188.853	0	11	11	0	10	11	11-	75	66	7
44	1.92295	5.61E-29	.041	1743.197	1	11	11	1	10	11	11-	75	66	7

Table I (Cont'd)

OXYGENEXIST ABSORPTION LINE PARAMETERS FOR MOLECULAR OXYGEN ISOTOPES (AFGL FORMAT

	FREQ	STRENGTH	WIDTH	E''	V'	J'	K'	V''	J''	K''	ID	DATE	ISO	NO
45	1.92298	2.21E-28	.041	179.048	0	11	11	0	10	11	11-	75	68	7
46	1.93133	1.03E-28	.047	8.025	0	2	2	0	3	2	2+	75	68	7
47	1.93361	2.36E-28	.042	149.187	0	10	10	0	9	10	10-	75	68	7
48	1.94488	2.46E-28	.043	122.036	0	9	9	0	8	9	9-	75	68	7
49	1.94548	1.22E-25	.043	128.492	0	9	9	0	8	9	9-	75	66	7
50	1.94764	6.33E-29	.043	1683.497	1	9	9	1	8	9	9-	75	66	7
51	1.94957	7.55E-26	.044	16.388	0	3	3	0	4	3	3+	75	66	7
52	1.95657	1.48E-28	.044	16.146	0	3	3	0	4	3	3+	75	68	7
53	1.95705	2.50E-28	.044	97.595	0	8	8	0	7	8	8-	75	68	7
54	1.96204	3.92E-29	.044	1572.612	1	3	3	1	4	3	3+	75	66	7
55	1.97052	2.48E-28	.044	75.865	0	7	7	0	6	7	7-	75	68	7
56	1.97351	1.26E-25	.044	79.607	0	7	7	0	6	7	7-	75	66	7
57	1.97549	1.87E-28	.043	26.989	0	4	4	0	5	4	4+	75	68	7
58	1.97649	6.48E-29	.044	1635.147	1	7	7	1	6	7	7-	75	66	7
59	1.98602	2.39E-28	.044	56.845	0	6	6	0	5	6	6-	75	68	7
60	1.98774	1.11E-25	.042	42.224	0	5	5	0	6	5	5+	75	66	7
61	1.99103	2.19E-28	.042	40.550	0	5	5	0	6	5	5+	75	68	7
62	2.00064	5.80E-29	.042	1598.164	1	5	5	1	6	5	5+	75	66	7
63	2.00455	2.44E-28	.041	56.827	0	6	6	0	7	6	6+	75	68	7
64	2.00491	2.21E-28	.044	40.536	0	5	5	0	4	5	5-	75	68	7
65	2.01159	1.13E-25	.044	42.200	0	5	5	0	4	5	5-	75	66	7
66	2.01509	5.84E-29	.044	1598.149	1	5	5	1	4	5	5-	75	66	7
67	2.01589	1.31E-25	.041	79.565	0	7	7	0	8	7	7+	75	66	7
68	2.01677	2.61E-28	.041	75.819	0	7	7	0	8	7	7+	75	68	7
69	2.02811	2.69E-28	.041	97.524	0	8	8	0	9	8	8+	75	68	7
70	2.02949	6.85E-29	.041	1635.094	1	7	7	1	8	7	7+	75	66	7
71	2.03011	1.95E-28	.045	26.934	0	4	4	0	3	4	4-	75	68	7
72	2.03881	2.71E-28	.040	121.942	0	9	9	0	10	9	9+	75	68	7
73	2.03976	1.35E-25	.040	128.398	0	9	9	0	10	9	9+	75	66	7
74	2.04904	2.65E-28	.039	149.072	0	10	10	0	11	10	10+	75	68	7
75	2.05418	7.06E-29	.040	1683.390	1	9	9	1	10	9	9+	75	66	7
76	2.05892	2.54E-28	.039	178.912	0	11	11	0	12	11	11+	75	68	7
77	2.06143	1.25E-25	.039	188.714	0	11	11	0	12	11	11+	75	66	7
78	2.06853	2.38E-28	.039	211.461	0	12	12	0	13	12	12+	75	68	7
79	2.06938	1.61E-28	.047	16.033	0	3	3	0	2	3	3-	75	68	7
80	2.07672	6.55E-29	.039	1743.043	1	11	11	1	12	11	11+	75	66	7
81	2.07792	2.18E-28	.038	246.718	0	13	13	0	14	13	13+	75	68	7
82	2.08181	1.05E-25	.038	260.501	0	13	13	0	14	13	13+	75	66	7
83	2.08432	8.41E-26	.047	16.253	0	3	3	0	2	3	3-	75	66	7
84	2.08715	1.97E-28	.036	284.681	0	14	14	0	15	14	14+	75	68	7
85	2.08728	4.32E-29	.047	1572.486	1	3	3	1	2	3	3-	75	66	7
86	2.09623	1.74E-28	.034	325.350	0	15	15	0	16	15	15+	75	68	7
87	2.09798	5.56E-29	.038	1814.041	1	13	13	1	14	13	13+	75	66	7
88	2.10139	8.23E-26	.034	343.748	0	15	15	0	16	15	15+	75	66	7
89	2.10519	1.52E-28	.035	368.722	0	16	16	0	17	16	16+	75	68	7
90	2.11406	1.30E-28	.036	414.795	0	17	17	0	18	17	17+	75	68	7
91	2.11844	4.37E-29	.034	1896.373	1	15	15	1	16	15	15+	75	66	7
92	2.12042	5.97E-26	.036	438.442	0	17	17	0	18	17	17+	75	66	7
93	2.12285	1.09E-28	.036	463.569	0	18	18	0	19	18	18+	75	68	7
94	2.13158	9.03E-29	.035	515.041	0	19	19	0	20	19	19+	75	68	7

Table I (Cont'd)

OXYGENEXIST ABSORPTION LINE PARAMETERS FOR MOLECULAR OXYGEN ISOTOPES (AFCRL FORMAT)

	FREQ	STRENGTH	WIDTH	E''	V'	J'	K'	V''	J''	K''	ID	DATE	ISO	MO
95	2.13836	3.19E-29	.036	1990.025	1	17	17	1	18	17	17+	75	66	7
96	2.13907	4.04E-26	.035	544.566	0	19	19	0	20	19	19+	75	66	7
97	2.14024	7.35E-29	.035	569.208	0	20	20	0	21	20	20+	75	68	7
98	2.14886	5.90E-29	.035	626.070	0	21	21	0	22	21	21+	75	68	7
99	2.15239	1.18E-28	.048	7.804	0	2	2	0	1	2	2-	75	68	7
100	2.15744	4.66E-29	.034	685.624	0	22	22	0	23	22	22+	75	68	7
101	2.15746	2.56E-26	.035	662.103	0	21	21	0	22	21	21+	75	66	7
102	2.15790	2.17E-29	.035	2094.982	1	19	19	1	20	19	19+	75	66	7
103	2.16598	3.62E-29	.032	747.867	0	23	23	0	24	23	23+	75	68	7
104	2.17450	2.78E-29	.032	812.798	0	24	24	0	25	24	24+	75	68	7
105	2.17564	1.52E-26	.032	791.034	0	23	23	0	24	23	23+	75	66	7
106	2.17715	1.39E-29	.035	2211.225	1	21	21	1	22	21	21+	75	66	7
107	2.18298	2.10E-29	.032	880.413	0	25	25	0	26	25	25+	75	68	7
108	2.19145	1.56E-29	.032	950.711	0	26	26	0	27	26	26+	75	68	7
109	2.19368	8.49E-27	.032	931.339	0	25	25	0	26	25	25+	75	66	7
110	2.19619	8.29E-30	.032	2338.737	1	23	23	1	24	23	23+	75	66	7
111	2.19989	1.14E-29	.032	1023.688	0	27	27	0	28	27	27+	75	68	7
112	2.20832	8.28E-30	.032	1099.341	0	28	28	0	29	28	28+	75	68	7
113	2.21160	4.45E-27	.032	1082.994	0	27	27	0	28	27	27+	75	66	7
114	2.21506	4.66E-30	.032	2477.495	1	25	25	1	26	25	25+	75	66	7
115	2.21674	5.90E-30	.032	1177.668	0	29	29	0	30	29	29+	75	68	7
116	2.22514	4.15E-30	.032	1258.667	0	30	30	0	31	30	30+	75	68	7
117	2.22943	2.20E-27	.032	1245.975	0	29	29	0	30	29	29+	75	66	7
118	2.24720	1.02E-27	.032	1420.255	0	31	31	0	32	31	31+	75	66	7
119	2.26492	4.48E-28	.032	1605.806	0	33	33	0	34	33	33+	75	66	7
120	2.28260	1.85E-28	.032	1802.598	0	35	35	0	36	35	35+	75	66	7
121	2.30026	7.24E-29	.032	2010.599	0	37	37	0	38	37	37+	75	66	7
122	2.31789	2.67E-29	.032	2229.774	0	39	39	0	40	39	39+	75	66	7
123	2.33551	9.29E-30	.032	2460.088	0	41	41	0	42	41	41+	75	66	7
124	3.96108	1.00E-25	.050	0.000	0	1	1	0	0	1	1-	75	66	7
125	3.96140	1.94E-28	.050	0.563	0	1	1	0	0	1	1-	75	68	7
126	3.97713	5.17E-29	.050	1556.378	1	1	1	1	0	1	1-	75	66	7
127	7.80360	2.91E-28	.050	0.000	0	1	2	0	1	0	SG	75	68	7
128	9.95599	1.67E-28	.050	0.000	0	2	2	0	1	0	SH	75	68	7
129	11.50856	4.25E-29	.048	4.525	0	2	3	0	1	1	SF	75	68	7
130	12.13118	1.14E-29	.048	1560.355	1	2	3	1	1	1	SF	75	66	7
131	12.29178	2.22E-26	.048	3.961	0	2	3	0	1	1	SF	75	66	7
132	13.40060	4.72E-28	.045	2.633	0	2	3	0	2	1	SG	75	68	7
133	14.02102	1.25E-28	.045	1558.465	1	2	3	1	2	1	SG	75	66	7
134	14.16858	2.43E-29	.045	2.084	0	2	3	0	2	1	SG	75	66	7
135	15.46998	2.05E-28	.045	2.633	0	3	3	0	2	1	SH	75	68	7
136	16.10831	5.38E-29	.045	1558.465	1	3	3	1	2	1	SH	75	66	7
137	16.25289	1.04E-25	.045	2.084	0	3	3	0	2	1	SH	75	66	7
138	16.97828	8.41E-29	.048	9.956	0	3	4	0	2	2	SF	75	68	7
139	18.90961	6.35E-28	.047	8.025	0	3	4	0	3	2	SG	75	68	7
140	20.93973	2.40E-28	.047	8.025	0	4	4	0	3	2	SH	75	68	7
141	22.43321	1.22E-28	.045	18.103	0	4	5	0	3	3	SF	75	68	7
142	23.57570	3.24E-29	.045	1574.574	1	4	5	1	3	3	SF	75	66	7
143	23.86295	6.28E-26	.045	18.337	0	4	5	0	3	3	SF	75	66	7
144	24.38978	7.75E-28	.044	16.146	0	4	5	0	4	3	SG	75	68	7

Table I (Cont'd)

OXYGENEXIST ABSORPTION LINE PARAMETERS FOR MOLECULAR OXYGEN ISOTOPES (AFCRL FORMAT)

	FREQ	STRENGTH	WIDTH	E''	V'	J'	K'	V''	J''	K''	ID	DATE	ISO	MO
145	25.53774	2.05E-28	.044	1572.612	1	4	5	1	4	3	SG	75	66	7
146	25.81252	3.96E-25	.044	16.388	0	4	5	0	4	3	SG	75	66	7
147	26.39469	2.69E-28	.044	16.146	0	5	5	0	4	3	SH	75	68	7
148	27.55283	7.08E-29	.044	1572.612	1	5	5	1	4	3	SH	75	68	7
149	27.82411	1.37E-25	.044	16.388	0	5	5	0	4	3	SH	75	66	7
150	27.88090	1.53E-28	.044	28.964	0	5	6	0	4	4	SF	75	68	7
151	29.85639	8.87E-28	.043	26.989	0	5	6	0	5	4	SG	75	68	7
152	31.84241	2.92E-28	.043	26.989	0	6	6	0	5	4	SH	75	68	7
153	33.32407	1.78E-28	.043	42.541	0	6	7	0	5	5	SF	75	68	7
154	34.98245	4.71E-29	.043	1600.164	1	6	7	1	5	5	SF	75	68	7
155	35.31509	9.69E-28	.042	40.550	0	6	7	0	6	5	SG	75	66	7
156	35.39530	9.10E-26	.043	44.212	0	6	7	0	5	5	SF	75	68	7
157	36.98309	2.55E-28	.042	1598.164	1	6	7	1	6	5	SG	75	66	7
158	37.28562	3.06E-28	.042	40.550	0	7	7	0	6	5	SH	75	66	7
159	37.38305	4.91E-25	.042	42.224	0	6	7	0	6	5	SG	75	68	7
160	38.76386	1.96E-28	.043	58.831	0	7	8	0	6	6	SF	75	66	7
161	38.95558	8.01E-29	.042	1598.164	1	7	7	1	6	5	SH	75	68	7
162	39.35655	1.54E-25	.042	42.224	0	7	7	0	6	5	SH	75	66	7
163	40.76842	1.02E-27	.041	56.827	0	7	8	0	7	6	SG	75	66	7
164	42.72546	3.13E-28	.041	56.827	0	8	8	0	7	6	SH	75	68	7
165	44.20080	2.07E-28	.042	77.835	0	8	9	0	7	7	SF	75	68	7
166	46.21758	1.04E-27	.041	75.819	0	8	9	0	8	7	SG	75	68	7
167	46.37341	5.40E-29	.042	1637.123	1	8	9	1	7	7	SF	75	68	7
168	46.91156	1.04E-25	.042	81.581	0	8	9	0	7	7	SF	75	66	7
169	48.16245	3.12E-28	.041	75.819	0	9	9	0	8	7	SH	75	66	7
170	48.40290	2.71E-28	.041	1635.094	1	8	9	1	8	7	SG	75	68	7
171	48.92745	5.22E-25	.041	79.565	0	8	9	0	8	7	SG	75	66	7
172	49.63509	2.11E-28	.042	99.552	0	9	10	0	8	8	SF	75	66	7
173	50.35054	8.09E-29	.041	1635.094	1	9	9	1	8	7	SH	75	68	7
174	50.87292	1.56E-25	.041	79.565	0	9	9	0	8	7	SH	75	66	7
175	51.66320	1.03E-27	.041	97.524	0	9	10	0	9	8	SG	75	66	7
176	53.596[illegible]1	3.04E-28	.041	97.524	0	10	10	0	9	8	SH	75	68	7
177	55.06678	2.08E-28	.041	123.981	0	10	11	0	9	9	SF	75	68	7
178	57.10558	1.00E-27	.040	121.942	0	10	11	0	10	9	SG	75	68	7
179	57.75231	5.37E-29	.041	1685.444	1	10	11	1	9	9	SF	75	68	7
180	58.41563	1.03E-25	.041	130.438	0	10	11	0	9	9	SF	75	66	7
181	59.02856	2.90E-28	.040	121.942	0	11	11	0	10	9	SH	75	66	7
182	59.80650	2.58E-28	.040	1683.390	1	10	11	1	10	9	SG	75	68	7
183	60.45539	4.95E-25	.040	128.398	0	10	11	0	10	9	SG	75	66	7
184	60.49582	2.01E-28	.041	151.121	0	11	12	0	10	10	SF	75	66	7
185	61.72944	7.45E-29	.040	1683.390	1	11	11	1	10	9	SH	75	68	7
186	62.37713	1.43E-25	.040	128.398	0	11	11	0	10	9	SH	75	66	7
187	62.54486	9.49E-28	.039	149.072	0	11	12	0	11	10	SG	75	66	7
188	64.45768	2.72E-28	.039	149.072	0	12	12	0	11	10	SH	75	68	7
189	65.92213	1.89E-28	.041	180.971	0	12	13	0	11	11	SF	75	68	7
190	67.98106	8.82E-28	.039	178.912	0	12	13	0	12	11	SG	75	68	7
191	69.11929	4.80E-29	.041	1745.120	1	12	13	1	11	11	SF	75	68	7
192	69.88407	2.50E-28	.039	178.912	0	13	13	0	12	11	SH	75	66	7
193	69.90770	9.19E-26	.041	190.775	0	12	13	0	11	11	SF	75	68	7
194	71.19601	2.24E-28	.039	1743.043	1	12	13	1	12	11	SG	75	66	7

Table I (Cont'd)

OXYGENEX.ST ABSORPTION LINE PARAMETERS FOR MOLECULAR OXYGEN ISOTOPES (AFCRL FORMAT)

	FREQ	STRENGTH	WIDTH	E''	V'	J'	K'	V''	J''	K''	ID	DATE	ISO	MO
195	71.34558	1.74E-28	.040	213.530	0	13	14	0	12	12	SF	75	68	7
196	71.96913	4.28E-25	.039	188.714	0	12	13	0	12	11	SG	75	66	7
197	73.09642	6.32E-29	.039	1743.043	1	13	13	1	12	11	SH	75	66	7
198	73.41411	8.03E-28	.039	211.461	0	13	14	0	13	12	SG	75	68	7
199	73.86939	1.21E-25	.039	188.714	0	13	13	0	12	11	SH	75	66	7
200	75.30761	2.25E-28	.039	211.461	0	14	14	0	13	12	SH	75	68	7
201	76.76602	1.57E-28	.038	248.796	0	14	15	0	13	13	SF	75	68	7
202	78.84394	7.18E-28	.038	246.718	0	14	15	0	14	13	SG	75	68	7
203	80.47340	3.92E-29	.038	1816.139	1	14	15	1	13	13	SF	75	66	7
204	80.72815	2.00E-28	.038	246.718	0	15	15	0	14	13	SH	75	68	7
205	81.38685	7.48E-26	.038	262.583	0	14	15	0	13	13	SF	75	66	7
206	82.18328	1.39E-28	.038	286.769	0	15	16	0	14	14	SF	75	68	7
207	82.57138	1.79E-28	.038	1814.041	1	14	15	1	14	13	SG	75	66	7
208	83.46866	3.41E-25	.038	260.501	0	14	15	0	14	13	SG	75	66	7
209	84.27043	6.30E-28	.036	284.681	0	15	16	0	15	14	SG	75	68	7
210	84.45053	4.97E-29	.038	1814.041	1	15	15	1	14	13	SH	75	66	7
211	85.34874	9.46E-26	.038	260.501	0	15	15	0	14	13	SH	75	66	7
212	86.14551	1.74E-28	.036	284.681	0	16	16	0	15	14	SH	75	68	7
213	87.59720	1.21E-28	.036	327.446	0	16	17	0	15	15	SF	75	68	7
214	89.69343	5.44E-28	.034	325.350		16	17	0	16	15	SG	75	68	7
215	91.55954	1.49E-28	.034	325.350		17	17	0	16	15	SH	75	68	7
216	91.81322	2.96E-29	.036	1898.492	.	16	17	1	15	15	SF	75	66	7
217	92.85169	5.62E-26	.036	345.850	0	16	17	0	15	15	SF	75	66	7
218	93.00758	1.03E-28	.037	370.827	0	17	18	0	16	16	SF	75	68	7
219	93.93166	1.33E-28	.034	1896.373	1	16	17	1	16	15	SG	75	66	7
220	94.95307	2.52E-25	.034	343.748	0	16	17	0	16	15	SG	75	66	7
221	95.11278	4.61E-28	.035	368.722	0	17	18	0	17	16	SG	75	68	7
222	95.79035	3.65E-29	.034	1896.373	1	17	17	1	16	15	SH	75	66	7
223	96.81382	6.91E-26	.034	343.748	0	17	17	0	16	15	SH	75	66	7
224	96.97004	1.26E-28	.035	368.722	0	18	18	0	17	16	SH	75	68	7
225	98.41425	8.67E-29	.037	416.909	0	18	19	0	17	17	SF	75	68	7
226	100.52832	3.85E-28	.036	414.795	0	18	19	0	18	17	SG	75	68	7
227	102.37684	1.05E-28	.036	414.795	0	19	19	0	18	17	SH	75	68	7
228	103.13716	2.08E-29	.037	1992.164	1	18	19	1	17	17	SF	75	66	7
229	103.81702	7.16E-29	.037	465.692	0	19	20	0	18	18	SF	75	68	7
230	104.30063	3.92E-26	.037	440.562	0	18	19	0	17	17	SF	75	66	7
231	105.27552	9.23E-29	.036	1990.025	1	18	19	1	18	17	SG	75	66	7
232	105.93987	3.17E-28	.036	463.569	0	19	20	0	19	18	SG	75	68	7
233	106.42105	1.74E-25	.036	438.442	0	18	19	0	18	17	SG	75	66	7
234	107.11429	2.50E-29	.036	1990.025	1	19	19	1	18	17	SH	75	66	7
235	107.77973	8.56E-29	.036	463.569	0	20	20	0	19	18	SH	75	68	7
236	108.26304	4.72E-26	.036	438.442	0	19	19	0	18	17	SH	75	66	7
237	109.21568	5.82E-29	.036	517.172	0	20	21	0	19	19	SF	75	68	7
238	111.34725	2.56E-28	.035	515.041	0	20	21	0	20	19	SG	75	68	7
239	113.17852	6.90E-29	.035	515.041	0	21	21	0	20	19	SH	75	68	7
240	114.44353	1.36E-29	.036	2097.140	1	20	21	1	19	19	SF	75	66	.
241	114.61004	4.65E-29	.036	571.349	0	21	22	0	20	20	SF	75	68	7
242	115.73199	2.56E-26	.036	546.705	0	20	21	0	19	19	SF	75	66	7
243	116.60142	5.99E-29	.035	2094.982	1	20	21	1	20	19	SG	75	66	7
244	116.75028	2.04E-28	.035	569.208	0	21	22	0	21	20	SG	75	68	7

Table I (Cont'd)

OXYGENEXIST ABSORPTION LINE PARAMETERS FOR MOLECULAR OXYGEN ISOTOPES (AFCRL FORMAT)

	FREQ	STRENGTH	WIDTH	E''	V'	J'	K'	V''	J''	K''	IO	DATE	ISO	MO
245	117.87106	1.13E-25	.035	544.566	0	20	21	0	20	19	SG	75	66	7
246	118.42066	1.61E-29	.035	2094.982	1	21	21	1	20	19	SH	75	66	7
247	118.57303	5.47E-29	.035	569.208	0	22	22	0	21	20	SH	75	68	7
248	119.69469	3.02E-26	.035	544.566	0	21	21	0	20	19	SH	75	66	7
249	119.99990	3.66E-29	.035	628.219	0	22	23	0	21	21	SF	75	68	7
250	122.14877	1.60E-28	.035	626.070	0	22	23	0	22	21	SG	75	68	7
251	123.96305	4.28E-29	.035	626.070	0	23	23	0	22	21	SH	75	68	7
252	125.38508	2.84E-29	.036	687.782	0	23	24	0	22	22	SF	75	68	7
253	125.73056	8.35E-30	.035	2213.402	1	22	23	1	21	21	SF	75	66	7
254	127.14400	1.56E-26	.035	664.261	0	22	23	0	21	21	SF	75	66	7
255	127.54252	1.24E-28	.034	685.624	0	23	24	0	23	22	SG	75	68	7
256	127.90771	3.64E-29	.035	2211.225	1	22	23	1	22	21	SG	75	66	7
257	129.30146	6.79E-26	.035	662.103	0	22	23	0	22	21	SG	75	66	7
258	129.34838	3.30E-29	.034	685.624	0	24	24	0	23	22	SH	75	68	7
259	129.70769	9.73E-30	.035	2211.225	1	23	23	1	22	21	SH	75	66	7
260	130.76535	2.17E-29	.035	750.033	0	24	25	0	23	23	SF	75	68	7
261	131.10704	1.81E-26	.035	662.103	0	23	23	0	22	21	SH	75	66	7
262	132.93134	9.41E-29	.032	747.867	0	24	25	0	24	23	SG	75	68	7
263	134.72882	2.50E-29	.032	747.867	0	25	25	0	24	23	SH	75	68	7
264	136.14053	1.63E-29	.034	814.972	0	25	26	0	24	24	SF	75	68	7
265	136.99647	4.80E-30	.035	2340.933	1	24	25	1	23	23	SF	75	66	7
266	138.31503	7.06E-29	.032	812.798	0	25	26	0	25	24	SG	75	68	7
267	138.53489	8.90E-27	.035	793.210	0	24	25	0	23	23	SF	75	66	7
268	139.19266	2.08E-29	.032	2338.737	1	24	25	1	24	23	SG	75	66	7
269	140.10417	1.87E-29	.032	812.798	0	26	26	0	25	24	SH	75	68	7
270	140.71053	3.86E-26	.032	791.034	0	24	25	0	24	23	SG	75	66	7
271	140.97360	5.53E-30	.032	2338.737	1	25	25	1	24	23	SH	75	66	7
272	141.51041	1.21E-29	.032	882.596	0	26	27	0	25	25	SF	75	68	7
273	142.49829	1.02E-26	.032	791.034	0	25	25	0	24	23	SH	75	66	7
274	143.69339	5.22E-29	.032	880.413	0	26	27	0	26	25	SG	75	68	7
275	145.47423	1.38E-29	.032	880.413	0	27	27	0	26	25	SH	75	68	7
276	146.87478	8.85E-30	.032	952.902	0	27	28	0	26	26	SF	75	68	7
277	149.06623	3.81E-29	.032	950.711	0	27	28	0	27	26	SG	75	68	7
278	149.90285	4.78E-27	.032	933.533	0	26	27	0	25	25	SF	75	66	7
279	150.45451	1.12E-29	.032	2477.495	1	26	27	1	26	25	SG	75	66	7
280	150.83879	1.01E-29	.032	950.711	0	28	28	0	27	26	SH	75	68	7
281	152.09653	2.06E-26	.032	931.339	0	26	27	0	26	25	SG	75	66	7
282	152.23345	6.37E-30	.032	1025.887	0	28	29	0	27	27	SF	75	68	7
283	153.86664	5.44E-27	.032	931.339	0	27	27	0	26	25	SH	75	66	7
284	154.43335	2.74E-29	.032	1023.688	0	28	29	0	28	27	SG	75	68	7
285	156.19765	7.21E-30	.032	1023.688	0	29	29	0	28	27	SH	75	68	7
286	157.58621	4.52E-30	.032	1101.549	0	29	30	0	28	28	SF	75	68	7
287	159.79453	1.94E-29	.032	1099.341	0	29	30	0	29	28	SG	75	68	7
288	161.24605	2.41E-27	.032	1085.206	0	28	29	0	27	27	SF	75	66	7
289	161.55061	5.10E-30	.032	1099.341	0	30	30	0	29	28	SH	75	68	7
290	161.69148	5.68E-30	.032	2627.478	1	28	29	1	28	27	SG	75	66	7
291	163.45765	1.03E-26	.032	1082.994	0	28	29	0	28	27	SG	75	66	7
292	165.14960	1.35E-29	.032	1177.668	0	30	31	0	30	29	SG	75	68	7
293	165.21027	2.72E-27	.032	1082.994	0	29	29	0	28	27	SH	75	66	7
294	170.49833	9.33E-30	.032	1258.667	0	31	32	0	31	30	SG	75	68	7

F-1/306-3-14

Table I (Cont'd)

OXYGENEXIST ABSORPTION LINE PARAMETERS FOR MOLECULAR OXYGEN ISOTOPES (AFCRL FORMAT)

	FREQ	STRENGTH	WIDTH	E''	V'	J'	K'	V''	J''	K''	ID	DATE	ISO	MO
295	172.56267	1.15E-27	.032	1248.204	0	30	31	0	29	29	SF	75	66	7
296	174.79210	4.89E-27	.032	1245.975	0	30	31	0	30	29	SG	75	66	7
297	175.84053	6.34E-30	.032	1342.332	0	32	33	0	32	31	SG	75	66	7
298	176.52734	1.28E-27	.032	1245.975	0	31	31	0	30	29	SH	75	66	7
299	181.17599	4.25E-30	.032	1428.663	0	33	34	0	33	32	SG	75	66	7
300	183.85086	5.13E-28	.032	1422.502	0	32	33	0	31	31	SF	75	66	7
301	186.09807	2.18E-27	.032	1420.255	0	32	33	0	32	31	SG	75	66	7
302	187.81602	5.71E-28	.032	1420.255	0	33	33	0	32	31	SH	75	66	7
303	195.10879	2.17E-28	.032	1608.071	0	34	35	0	33	33	SF	75	66	7
304	197.37371	9.19E-28	.032	1605.806	0	34	35	0	34	33	SG	75	66	7
305	199.07447	2.40E-28	.032	1605.806	0	35	35	0	34	33	SH	75	66	7
306	206.33461	8.63E-29	.032	1804.881	0	36	37	0	35	35	SF	75	66	7
307	208.61722	3.65E-28	.032	1802.598	0	36	37	0	36	35	SG	75	66	7
308	210.30084	9.50E-29	.032	1802.598	0	37	37	0	36	35	SH	75	66	7
309	217.52647	3.25E-29	.032	2012.899	0	38	39	0	37	37	SF	75	66	7
310	219.82673	1.37E-28	.032	2010.599	0	38	39	0	38	37	SG	75	66	7
311	221.49328	3.56E-29	.032	2010.599	0	39	39	0	38	37	SH	75	66	7
312	228.68253	1.15E-29	.032	2232.092	0	40	41	0	39	39	SF	75	66	7
313	231.00042	4.86E-29	.032	2229.774	0	40	41	0	40	39	SG	75	66	7
314	232.64995	1.26E-29	.032	2229.774	0	41	41	0	40	39	SH	75	66	7
315	239.80093	3.88E-30	.032	2462.424	0	42	43	0	41	41	SF	75	66	7
316	242.13644	1.63E-29	.032	2460.088	0	42	43	0	42	41	SG	75	66	7
317	243.76899	4.21E-30	.032	2460.088	0	43	43	0	42	41	SH	75	66	7
318	253.23294	5.17E-30	.032	2701.504	0	44	45	0	44	43	SG	75	66	7

and Gordy[28] (Ref. 7 of T-1/306-3-14)[2] in the vibrational ground state (v = v' = v'' = 0), and on those of Albritton, et al.[26] (Ref. 5 of T-1/306-3-14)[2] in the first excited vibrational state (v = v' = v'' = 1) of $^{16}O_2$. The line-widths quoted (WIDTH) are nominal values adapted from a review article by Krupenie.[29] Units are as follows: frequency: cm^{-1}; integrated line strength at 296K: cm^{-1} per (molecule cm^{-2}); half-width at half-maximum absorption: cm^{-1} atm^{-1}; energy E'' of the lower state of the transition relative to the vibrational and rotational ground state: cm^{-1}; quantum numbers of upper (v', J', K') and lower (v'', J'', K'') states; shorthand identification of transition; month and year of date of computation (July 1975); isotope code (66 = $^{16}O^{16}O$, 68 = $^{16}O^{18}O$, 88 = $^{18}O^{18}O$); molecular constituent code (7 = oxygen). The format is identical with that of the AFCRL Atmospheric Absorption Line Parameters Compilation[4] with the exception that the frequency is given to five decimal places (F10.5 format) instead of three (F10.3).

The results have been discussed with AFCRL personnel, as well as with Drs. Strandberg, Mizushima, Steinbach, and Zare (respectively of MIT/RLE, Univ. of Colorado, AFOSR, and Columbia Univ.)[2] and a deck of punched cards containing the card-image records in the file listed in Table II was sent to AFCRL on 28 July 1975. (The computations of line strength made use of some unpublished results in Steinbach's thesis.[30]) The line widths must be viewed as preliminary,[2] and subject to update within a year.[31]

Fig. 1 gives a sample APL program used to generate the data, in this case the transition frequencies. Further details are contained in Ref. 2.

```
∇ SUBMM02;N;ENJ;ENJMINUS;ENJPLUS;AB0;AB1;AB2;AL1;AM1;BB1;BB2;BL11;BM0;BM1;MESS0;MESS1;MESS2;ARG1;EDF;EDG;EDH
  ⍝       THIS PROGRAM CALCULATES THE TRANSITION FREQUENCIES,
  ⍝ NUF, NUG, AND NUH (IN THE SUBMM REGION), AND THE ENERGIES
  ⍝ OF THE RESPECTIVE LOWER STATES, ELF, ELG, AND ELH,
  ⍝ ALL GIVEN IN INVERSE CM.  INPUTS REQUIRED: B0, B1, B2,
  ⍝ LAM0, LAM1, MU0, AND NINPUT.
  ⍝ (EXAMPLE: NINPUT←((2×⍳ 27)-1) PRODUCES 1 3 5 ...51 53.)
  'REFNO = ',REFNO
  'NINPUT:  ';NINPUT
  B1←-(|B1)
  B2←-(|B2)
  MU0←-(|MU0)
  MU1←-(|MU1)
  N←NINPUT,(NINPUT+2)
  ENJ←(B0×N×(N+1))+(B1×(N*2)×((N+1)*2))+(2×LAM0÷3)+(2×LAM1×N×(N+1)÷3)-(MU0+(MU1×N×(N+1)))
  ENJ←ENJ+(B2×(N*3)×((N+1)*3))
  ENN←((ρN)÷2)↑ENJ
  AB0←(N*2)+1-N
  AB1←(N*4)+(7×(N*2))+2-((2×(N*3))+(6×N))
  AB2←(N*6)+(18×(N*4))+(33×(N*2))+4-((3×(N*5))+(31×(N*3))+(18×N))
  AL1←(N*2)+4-N
  AM1←(7×(N*2))+4-(7×N)
  BB1←(4×(N*3))+(6×N)-((6×(N*2))+2)
  BB2←(6×(N*5))+(32×(N*3))+(18×N)-((15×(N*4))+(33×(N*2))+4)
  BL11←(6×N)-3
  BM0←N-0.5
  BM1←(2×(N*3))+(9×N)-((3×(N*2))+4)
  MESS0←(B0×AB0)+(B1×AB1)+(B2×AB2)-((LAM0÷3)+(LAM1×AL1÷3)+(3×MU0÷2)+(0.5×MU1×AM1))
  MESS1←(B0×((2×N)-1))+(B1×BB1)-((LAM0÷((2×N)-1))+((LAM1×AM1)÷BL11)+(MU0×BM0)+(0.5×MU1×BM1))
  MESS1←MESS1+(B2×BB2)
  MESS2←(LAM0)+(LAM1×AB0)
  ARG1←(MESS1*2)+(4×(MESS2*2)×N×(N-1)×(((2×N)-1)*¯2))
  ENJMINUS←MESS0+(ARG1*0.5)
  E10←MESS0+MESS1
  ENNMIN1←((ρN)÷2)↑ENJMINUS
  ENNMIN1[1]←E10[1]
  ENJPLUS←MESS0-(ARG1*0.5)
  ENNPLU1←((ρN)÷2)↓ENJPLUS
  ⍝ EDF, EDG, AND EDH ARE IN GIGAHERTZ
  EDF←(((ρN)÷2)↓ENJMINUS)-ENN
  EDG←(((ρN)÷2)↓ENJMINUS)-ENNPLU1
  EDH←(((ρN)÷2)↓ENJ)-ENNPLU1
  →(N[1]≠0)/CONTINUE
  ENNMIN1[2]←E10[2]
  E10[1]←ENN[1]←ENNMIN1[1]←ENNPLU1[1]
  EDF[1]←0
  CONTINUE:SPEEDOFLIGHT←29.9792458⍝  [GHZ PER INVERSE CM]
  ⍝ ELF, ELG, ELH, NUF, NUG, AND NUH ARE IN INVERSE CM.
  ELF←(ENN-E10[1])÷SPEEDOFLIGHT
  ELG←(ENNPLU1-E10[1])÷SPEEDOFLIGHT
  ELH←ELG
  NUF←EDF÷SPEEDOFLIGHT
  NUG←EDG÷SPEEDOFLIGHT
  NUH←EDH÷SPEEDOFLIGHT
∇
```

Fig. 1: Listing of APL function SUBMMO2

III. SLANT-PATH ABSORPTION MODEL (SLAM) DEVELOPMENT

As mentioned in Section II, one of the main objectives of the present RRI study has been the development of detailed predictions of molecular attenuation as a function of frequency and altitude. Because narrow-band sources in the millimeter and submillimeter wave regions are of interest, a frequency resolution of .001 $cm^{-1} \doteq 30$ MHz was chosen; this choice is compatible with the data resolution in the well-known AFCRL line parameters compilation.[4] Also, in the interest of allowing cross-checks with already-existing slant-path calculations (which heretofore have considered only water and (sometimes) ozone in the submillimeter region, and only water plus oxygen in the millimeter region), a single standard atmospheric model was chosen initially:[5] the Midlatitude Winter Model employed by McClatchey, et al.[32] To make the spectroscopic data as up-to-date as possible, the most recent version of the AFCRL computer tape containing the Atmospheric Absorption Line Parameters Compilation[4] was obtained;[33] as already discussed in Section II, this data was supplemented by line parameters developed at RRI for oxygen[2] and carbon monoxide[3] in the region below 250 cm^{-1}. (Other species known to be of importance in this spectral region at high altitude--on the basis of atmospheric emission spectra[20,22] and solar spectral studies[34,35]--are to be added at a later date.[5,9])

As to frequency coverage and data output format, it was realized from the outset[5] that the results must be useful for analyzing communications systems and other applications in this spectral region, not only at ground level, but also with transmitters and receivers at higher altitudes. Hence, emphasis has been placed on calculating the total attenuation (dB) down to the

ground and out into space at any given frequency, at the set of reasonably spaced atmospheric levels given in McClatchey, et al,[32] and in the following spectral regions:[1] the vicinity of the 60 GHz oxygen band,[7] the first three peaks in the submillimeter spectrum of $^{16}O_2$,[2,19-22,28,30] and their immediate neighborhood, and at the 337-μm HCN laser line.[32] In addition, the model was to be capable of predicting absorptions in the "window" regions wherever the sea-level attenuation is 3 dB/km or less.[5] This made it necessary to include not only the Lorentz[4,32] and Van Vleck-Weisskopf line profiles, but also the "kinetic" (Gross/Zhevakin-Naumov) line shapes as options. (For details, see Tech. Report T-2/306-3-14.[1]) To make the results readily understandable, provision was made for both tabular and graphical output, samples of which appear in Figs. 2 and 3 and in Table III (taken from Ref. 1). At each altitude, the <u>horizontal</u> attenuation (dB/km) as well as the attenuation <u>down</u> to the ground and <u>up</u> to space (dB) are given.

Since, at the present time,[1] only pressure broadening is considered, the program is only nominally valid from 0 to 100 km altitude; a more realistic range of validity is 0 to 40 km.[1] Extensions to Voigt-type profiles will extend the range of validity of the SLAM program in the near future to the higher altitudes,[5] particularly when more realistic water vapor profiles[36] than are used by McClatchey, et al[32] are included in the model at the same time.[5,9]

The principal uncertainty in the predictions (besides the obviously variable water vapor concentration) is tied up with the still-unresolved issue of the correct line-shape to use for the water vapor absorptions[1] as well as with the oxygen line widths and their pressure dependence.[2,7] As an illustration of the order of magnitude of the line-shape effect, Figs. 2 and 3 may be compared. Both refer to the 337-μm HCN laser line, one with a Van Vleck-Weisskopf profile,[32,37] the other with the

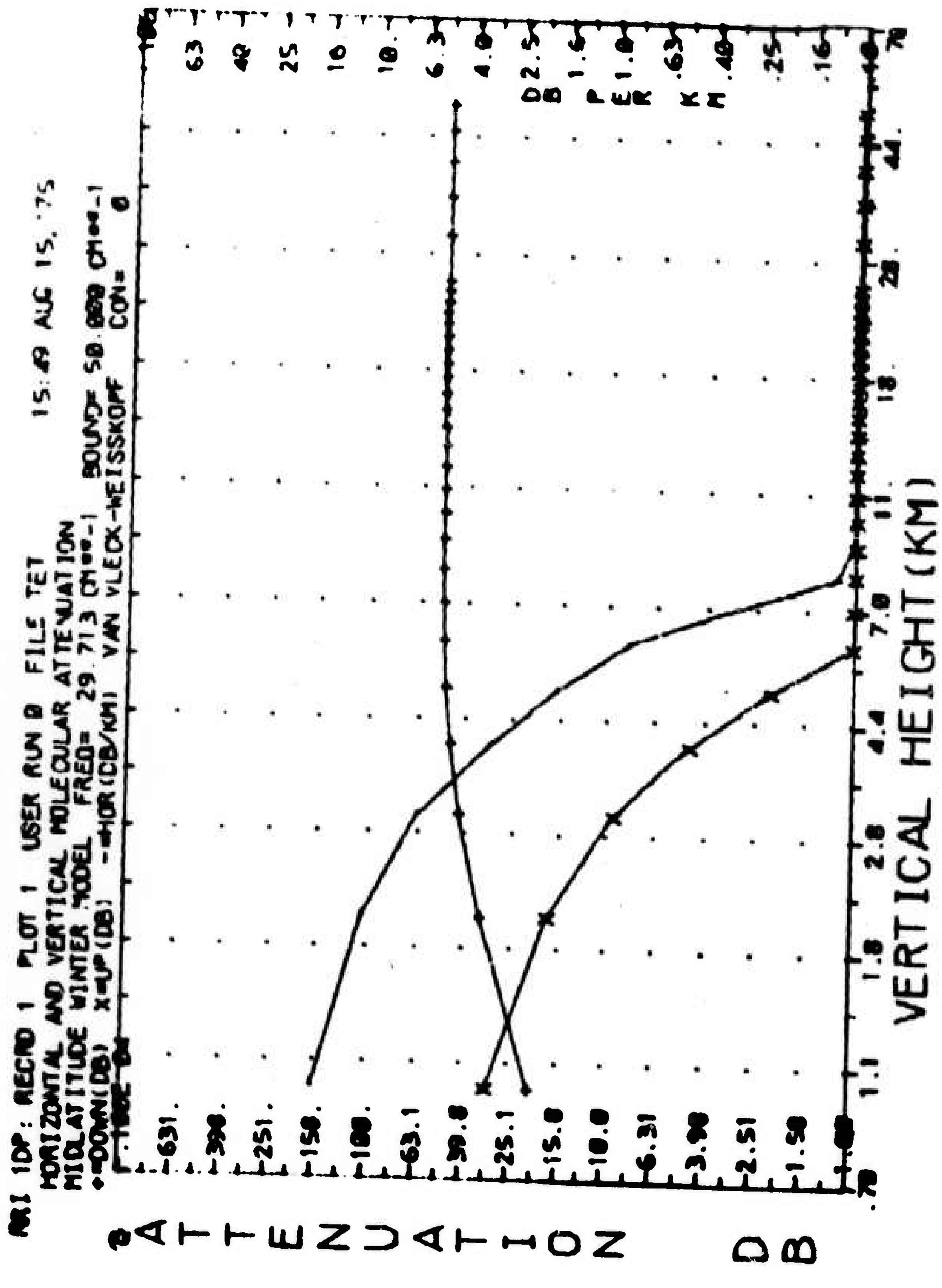

Fig. 2: SLAM Graphical Output at 337μm, VVW Profile

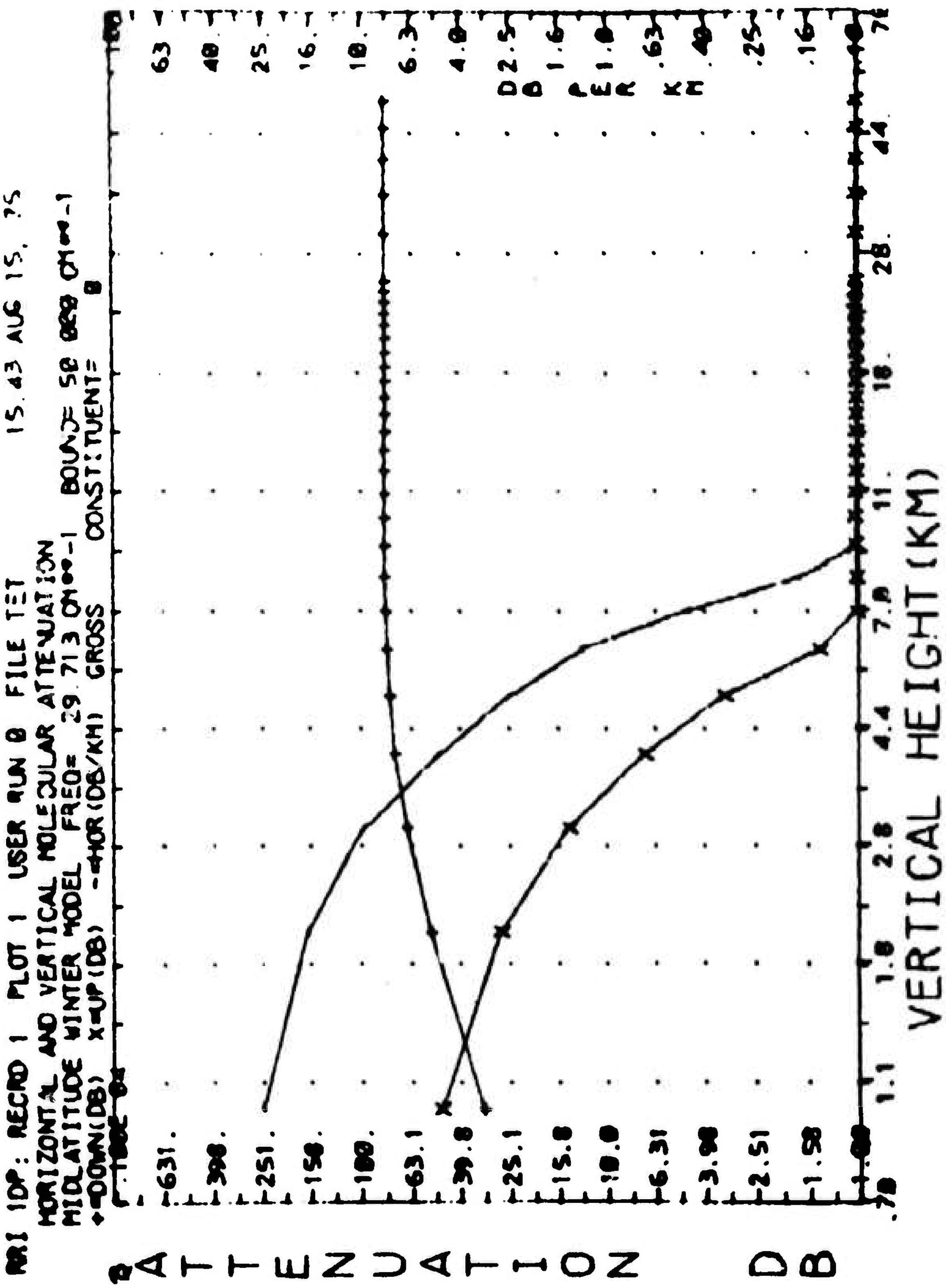

Fig. 3: SLAM Craphical Output at 337 μm, Gross Profile

Table III: SLAM Tabular Output

```
V1=    29.713V2=    29.714DV=       .001BOUND=     50.000
VBOT     -20.287VTOP       79.714GNU(1)=         .307GNU=      79.77411    2148
   3   29.7150    29.7740   VAN VLECK-WEISSKOPF PROFILE   CONSTITUENT=    0
FREQUENCY=    29.713
```

HEIGHT	HOR	DOWN	UP	HEIGHT	HOR	DOWN	UP
.000	.24939E 02	.00000E 00	.51358E 02	1.000	.16069E 02	.20504E 02	.30854E 02
2.000	.10424E 02	.33751E 02	.17607E 02	3.000	.62531E 01	.42089E 02	.92686E 01
4.000	.31301E 01	.46781E 02	.45770E 01	5.000	.16372E 01	.49165E 02	.21933E 01
6.000	.82126E 00	.50394E 02	.96408E 00	7.000	.30380E 00	.50956E 02	.40155E 00
8.000	.11578E 00	.51166E 02	.19177E 00	9.000	.50030E-01	.51249E 02	.10887E 00
10.000	.23170E-01	.51286E 02	.72281E-01	11.000	.18585E-01	.51306E 02	.51407E-01
12.000	.14319E-01	.51323E 02	.34958E-01	13.000	.56185E-02	.51333E 02	.24994E-01
14.000	.36835E-02	.51338E 02	.20355E-01	15.000	.28618E-02	.51341E 02	.17090E-01
16.000	.23424E-02	.51343E 02	.14496E-01	17.000	.19966E-02	.51346E 02	.12329E-01
18.000	.17078E-02	.51347E 02	.10483E-01	19.000	.15101E-02	.51349E 02	.88806E-02
20.000	.13340E-02	.51350E 02	.74615E-02	21.000	.11595E-02	.51352E 02	.62256E-02
22.000	.10219E-02	.51353E 02	.51422E-02	23.000	.85198E-03	.51354E 02	.42114E-02
24.000	.72934E-03	.51354E 02	.34332E-02	25.000	.63162E-03	.51355E 02	.27618E-02
30.000	.18219E-03	.51357E 02	.73242E-03	35.000	.44025E-04	.51358E 02	.16785E-03
40.000	.11466E-04	.51358E 02	.30518E-04	45.000	.23073E-05	.51358E 02	.00000E 00
50.000	.44352E-06	.51358E 02	.00000E 00	70.000	.49539E-09	.51358E 02	.00000E 00
100.000	.88210E-14	.51358E 02	.00000E 00				

```
FREQUENCY=    29.714
```

HEIGHT	HOR	DOWN	UP	HEIGHT	HOR	DOWN	UP
.000	.24960E 02	.00000E 00	.51410E 02	1.000	.16084E 02	.20522E 02	.30887E 02
2.000	.10435E 02	.33782E 02	.17628E 02	3.000	.62605E 01	.42130E 02	.92799E 01
4.000	.31341E 01	.46827E 02	.45826E 01	5.000	.16395E 01	.49214E 02	.21958E 01
6.000	.82251E 00	.50445E 02	.96477E 00	7.000	.30429E 00	.51008E 02	.40138E 00
8.000	.11596E 00	.51218E 02	.19127E 00	9.000	.50104E-01	.51302E 02	.10825E 00
10.000	.23195E-01	.51338E 02	.71609E-01	11.000	.18600E-01	.51359E 02	.50720E-01
12.000	.14325E-01	.51375E 02	.34271E-01	13.000	.56077E-02	.51385E 02	.24307E-01
14.000	.36699E-02	.51390E 02	.19669E-01	15.000	.28468E-02	.51393E 02	.16418E-01
16.000	.23259E-02	.51396E 02	.13840E-01	17.000	.19771E-02	.51398E 02	.11688E-01
18.000	.16845E-02	.51400E 02	.98724E-02	19.000	.14615E-02	.51401E 02	.83008E-02
20.000	.12979E-02	.51403E 02	.69122E-02	21.000	.11179E-02	.51404E 02	.57068E-02
22.000	.97265E-03	.51405E 02	.46692E-02	23.000	.80080E-03	.51406E 02	.37842E-02
24.000	.67729E-03	.51407E 02	.30518E-02	25.000	.57943E-03	.51407E 02	.24261E-02
30.000	.15702E-03	.51409E 02	.59509E-03	35.000	.35540E-04	.51410E 02	.12207E-03
40.000	.88126E-05	.51410E 02	.15259E-04	45.000	.17341E-05	.51410E 02	.00000E 00
50.000	.33035E-06	.51410E 02	.00000E 00	70.000	.41580E-09	.51410E 02	.00000E 00
100.000	.86743E-14	.51410E 02	.00000E 00				

"kinetic" profile. For comparison, Fig. 4 is presented, giving a low-resolution survey of the entire spectral range 0.1 μm to 10 cm, from the critical review by the late G. D. Lukes,[38] which includes representative measurements on the plot. As to the oxygen line widths,[2] part of the problem is that the experimental data do not agree very well with the sum-of-Lorentzians calculations near 1 atm in the microwave region.[7] Our SLAM output plots[1,9] based on the sum-of-Lorentzian approach agree well with the data in Figs. 5 and 6 taken from Ref. 39. The submillimeter line widths have never been directly measured, and only indirect information of low accuracy[19,20,22] is available.[2] With the recent development of workable interacting-line theories, it should soon be possible to improve the SLAM program to include them,[9] just as Liebe has recently done.[7]

Extensions to the SLAM program to dispersion calculations and turbulence prediction are possible, based on the well-known integral relationship between attenuation and dispersion,[9] for "any" assumed line profile. The dispersion results in Figs. 5 and 6 were developed on the basis of a Lorentzian line profile analysis, for example.[7,39]

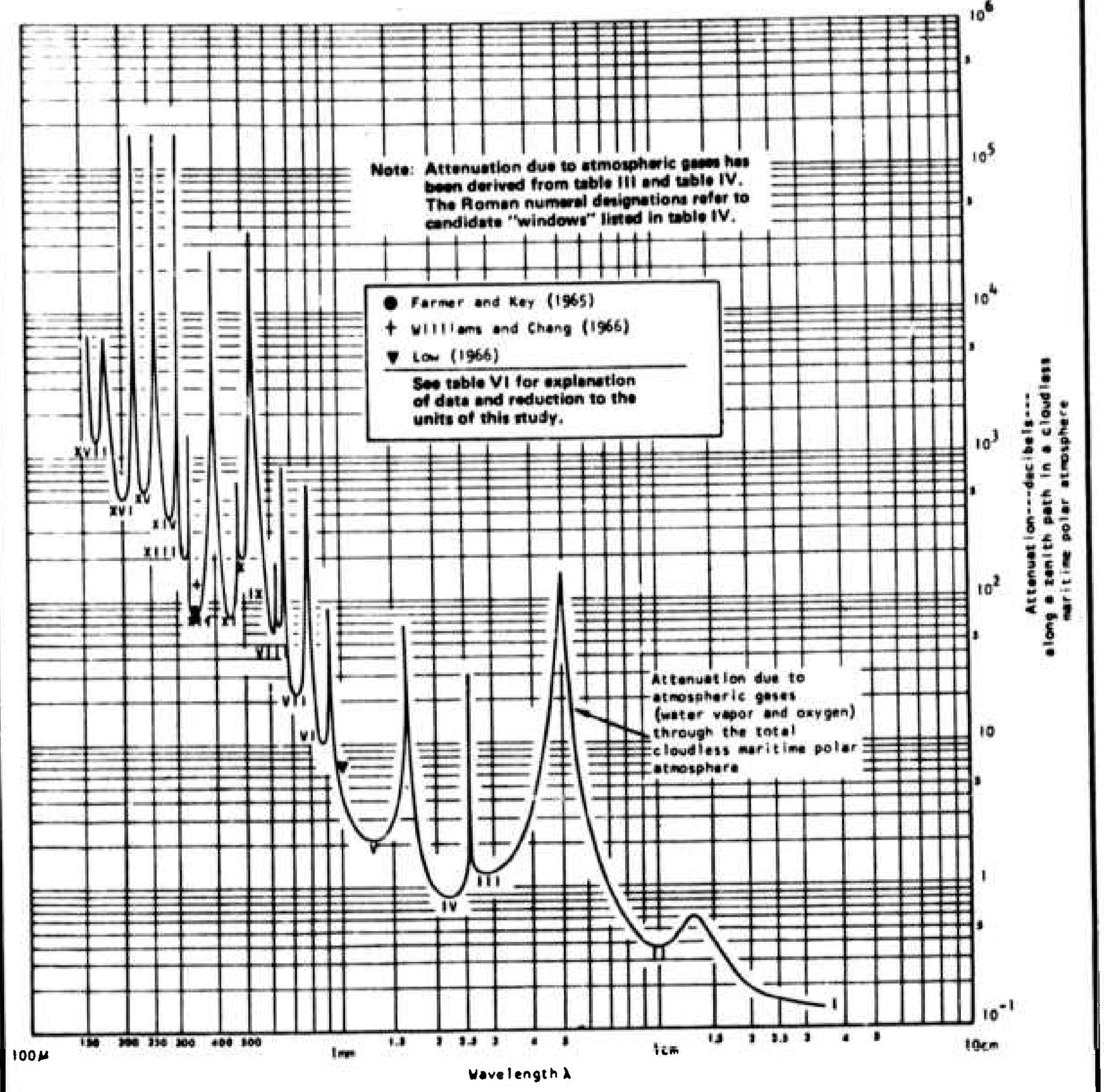

Fig. 4: Attenuation Due to Atmospheric Gases Along a Zenith Path Through a Cloudless Maritime Polar Atmosphere (After Lukes, Ref. 38.)

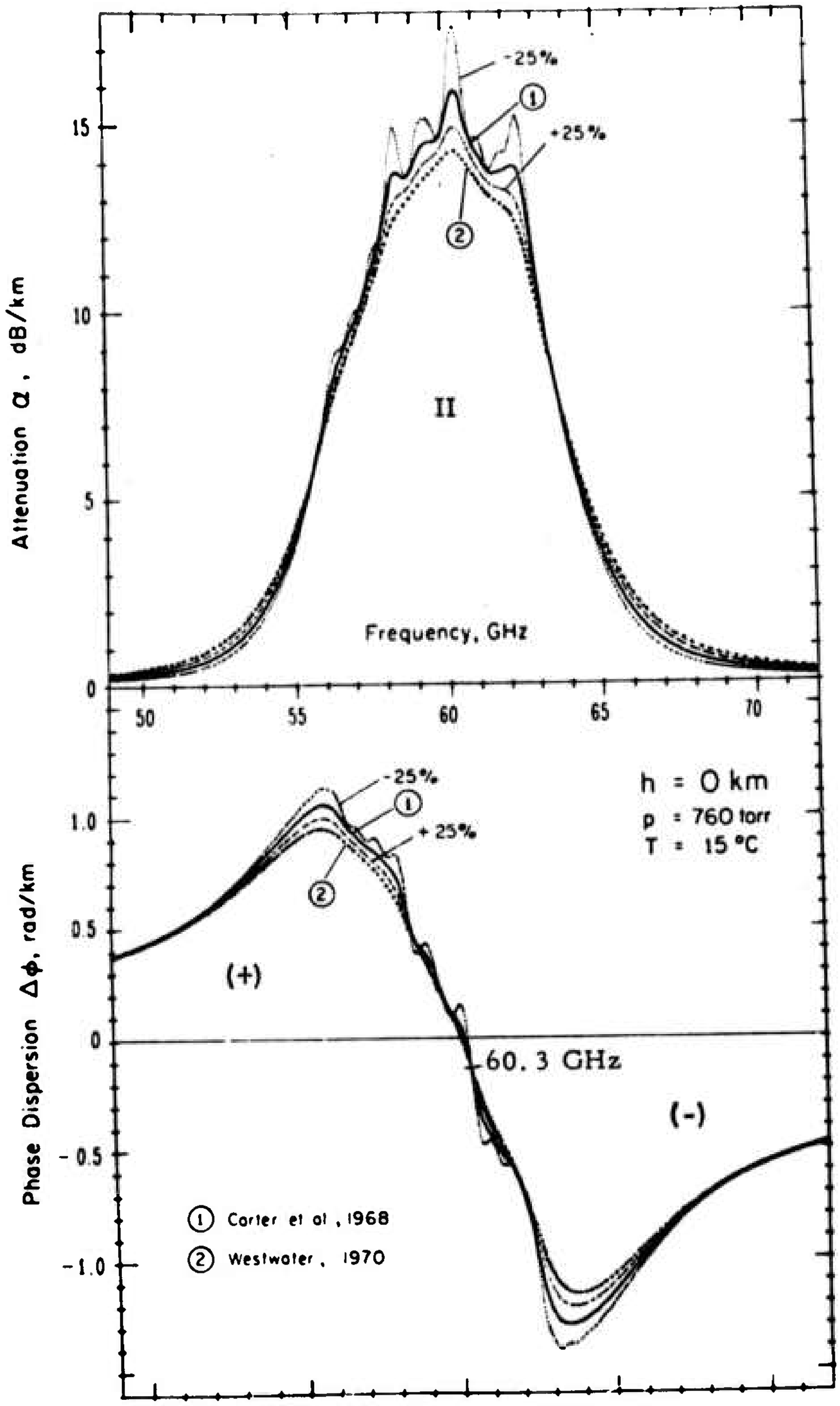

Fig. 5 Horizontal (homogeneous) transmissivity at sea level, h = 0 km. Variations are shown due to different linewidth values: (1) γ_1 = 666 MHz ± 25%, (2) γ_1 = 968 MHz. (After Liebe and Welch, Ref. 39.)

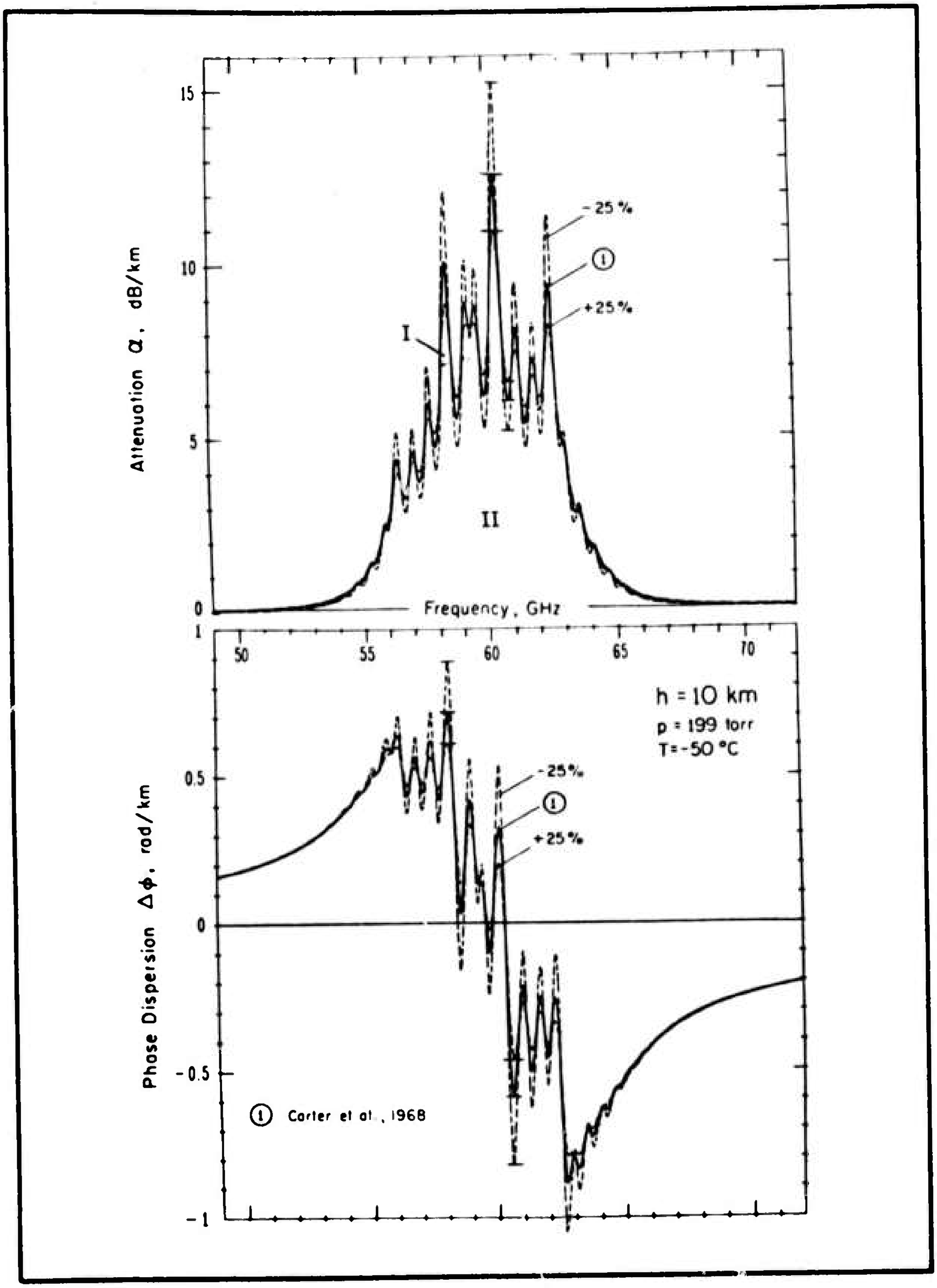

Fig. 6 Horizontal (homogeneous) transmissivity at h = 10 km (U.S. Std. Atm. 62). Variations are shown due to different linewidth values: ① γ_1=255 MHz ± 25%. (After Liebe and Welch, Ref. 39.)

IV. OTHER COMPUTER CALCULATIONS PERFORMED

As indicated in Section II, absorption line parameters for a number of trace species known to be of some importance as absorbers in the millimeter-to-submillimeter wave spectral region are required in order to correctly predict attenuation at altitudes above the tropopause. In view of a controversy in the literature concerning the degree of importance of carbon monoxide as an absorber [3,20,40-43] in this spectral region, and the simplicity of the molecule, it was decided to compute the CO line parameters first. Only the ground vibrational state was considered for the isotopic species: $^{12}C^{16}O$, $^{12}C^{17}O$, $^{12}C^{18}O$, and $^{13}C^{16}O$, and (in view of the low concentration) the hyperfine structure in $^{12}C^{17}O$ was ignored. The latest dipole moment value for $^{12}C^{16}O$ was used:[44] -0.10980(3) Debye units, whose uncertainty is much less than the earlier value[45] 0.112(5) D. For details concerning linewidths assumed and values chosen for B_0, D_0, and H_0, see Tech. Report T-3/306-3-14.[3] When the AFCRL criterion[4] for "Existing Intensity Minimum at T = 296K" is applied (1.9 E-23 cm^{-1} per molecule cm^{-2}), only lines of $^{12}C^{16}O$ remain in the list.[3]

As to the status of our computations of line parameters for other trace species as of 15 August 1975: Line positions only have been computed for $^{14}N^{16}O$ (dominant isotope of nitric oxide); subroutines for evaluations of the Wigner six-j symbols have been completed and tested, in preparation for computing the line strengths of the $^{16}O^{17}O$ lines in accordance with unpublished work[46] by Steinbach;[18] unpublished reports of work performed at the National Physical Laboratory, Teddington, England on nitric acid vapor and other trace species observed[20] in emission in the stratosphere have been received and studied.[47]

V. RESULTS OF LITERATURE SURVEY

The literature on atmospheric propagation of electromagnetic radiation with wavelengths in the millimeter and submillimeter region is scattered over a large number of incompletely indexed journals and reports. Starting with the past several years of Physics Abstracts and cover-to-cover searches of such journals as Izvestia V. U. Z. Radiofizika, J. Quant. Spectrosc. and Rad. Transfer, Infrared Physics, Radio Engineering and Electronic Physics, and Izvestia Acad. Sci. USSR, Atmospheric and Oceanic Physics over the past three years, over 1000 card-indexed citations were obtained. The subjects covered include not only absorption and emission measurements and predictions, dispersion calculations, etc., but also atmospheric models, trace-species spectroscopy (HNO_3, NO_2, SO_2, etc.), and *in situ* measurements of constituent concentrations vs. altitude. Aside from the references directly cited in support of other sections of this report, there would be no useful purpose served by merely listing author, title, and reference without comment for so disparate (yet voluminous) a collection. RRI has proposed the preparation of specialized bibliographies organized by subject and aimed at an audience of systems analysts, which would draw upon this collection.[9] One general comment is in order, however: the Russian literature on applications of submillimeter wave technology to meteorology and astrophysics has continued in a steady stream since 1963, but English-language translations are lately subject to a lag of more than two years.

The extensive British work on far-infrared Fourier-transform spectroscopy and its applications to stratospheric meteorology and astrophysics has been summarized recently in Ref. 20 (Fig. 7).

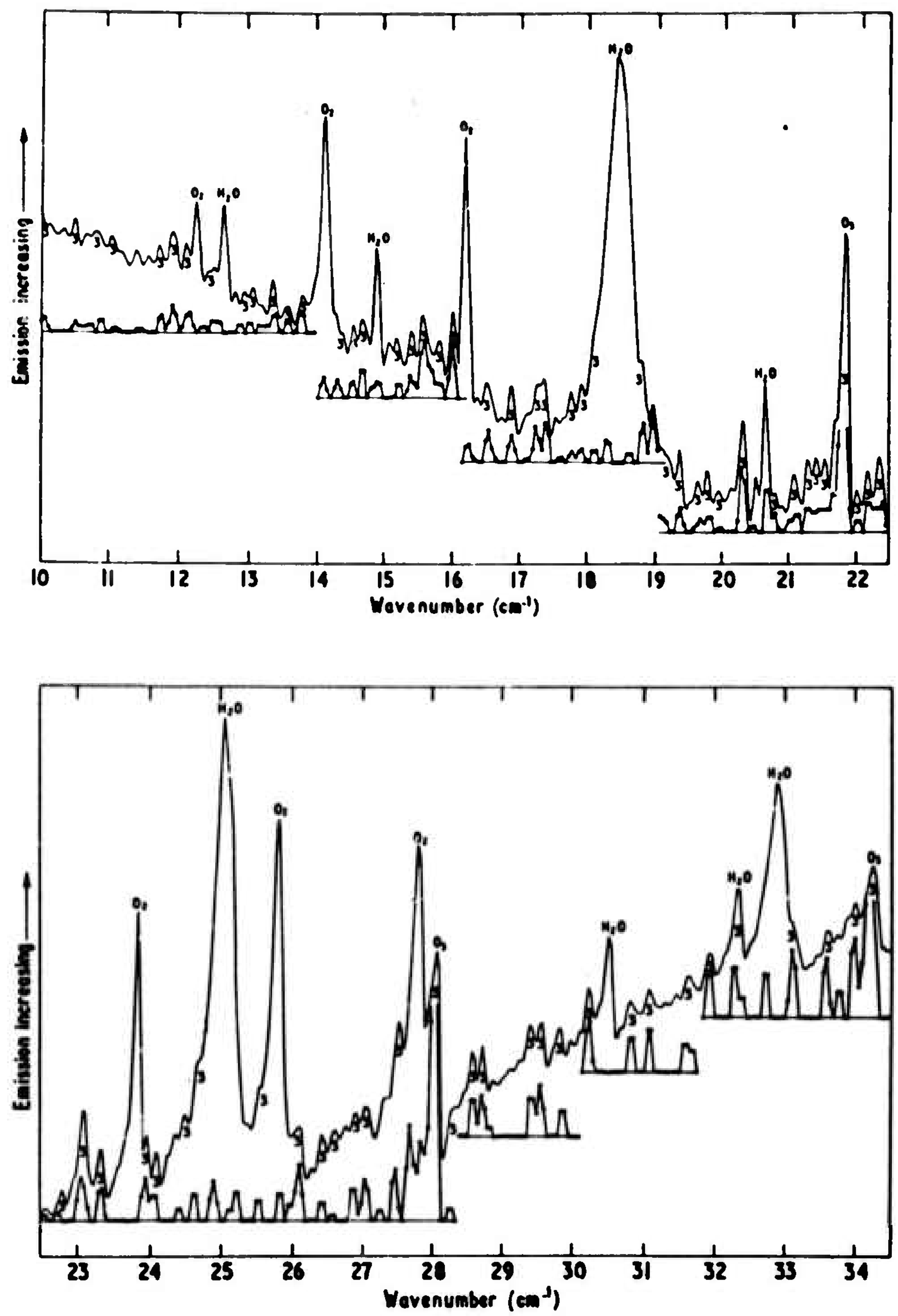

Fig. 7: Atmospheric Emission, 10-34 cm^{-1} (After Ref. 20) Resolution is 0.0625 cm^{-1}; taken at 12 km altitude, at zenith angle of 75°, from Comet 2E aircraft (UK).

Fig. 7 shows a typical atmospheric emission spectrum taken at an altitude of 12 km, with the emission lines of water, oxygen, and ozone clearly marked. A comparison synthetic spectrum of ozone is superimposed in the figure. Of course, since a high emissivity is indicative of a high absorptivity (albeit with a somewhat modified frequency-dependence), the peaks in the figure also indicate absorption peaks.

One final comment: reference is frequently made to a paper by Hall[48] which gives the water vapor absorption as a function of frequency. We wish to point out that, as noted by Falcone[49] and Emery[50,51] Hall made an unfortunate error in the frequency dependence which he attributed to the "kinetic" line shape. Thus, papers such as the one by Burch[52] which are based on the results of Hall[48] (or its unpublished predecessors) must be employed with caution.[1] Our Fig. 4, from the summary paper by Lukes,[38] does not suffer from this defect, since it takes cognizance of Bastin's work,[53] of which Emery's[51] is a refinement. Fig. 4 represents the best low-resolution display of the total zenith attenuation at sea level which has yet appeared in the literature, although the submillimeter spectrum of oxygen[2,19-22] is neglected. Tech. Report T-2/306-3-14 discusses in detail the relationship of our SLAM results with those in the literature.[1]

VI. RECOMMENDATIONS FOR IMPROVEMENT OF DATA BASE

In connection with Figs. 2 and 3, it was pointed out that the water vapor line-shape choice makes a substantial difference in the total attenuation predicted. Limited experimental data is available as a function of pressure [20,38,40,51] and near 1 atm the theory underestimates the attenuation by roughly a factor of two (in dB) when only the monomeric form of water is considered. The water dimer is clearly important as a source of additional attenuation at high pressure,[40] but the quantitative details are still controversial.[41-43] Molecular beam studies have recently been made of the microwave absorption by the dimer molecule, $(H_2O)_2$,[54] which have determined the bond lengths precisely, but still leave the bond angles uncertain.[55] Direct submillimeter-wave molecular-beam absorption studies are thus desirable, to determine where the bound states lie.[9,55] Further theoretical calculations should then be possible to determine the linewidths, and thereby put the subject of dimer absorption on a firmer foundation than at present.[56]

At high altitudes, the CIAP-related studies of the stratosphere[20,22,36] have produced emission data. The SLAM calculations should be cast into a form capable of predicting emission (not merely absorption) so as to compare observations against predictions. At altitudes below the tropopause, with which the CIAP program was hardly concerned,[36] measurements are desirable at selected frequencies, to act as a check on the various model computations, especially the oxygen linewidths and the water vapor line-shapes.[1,2,5,9]

From the discussion in Sections II through IV, it is clear

that continued effort is required to obtain reliable atmospheric absorption line parameters in the millimeter and submillimeter wave region for all of the trace species which have been identified in the recent stratospheric emission studies,[20,22,34-36] i. e., nitric acid (HNO_3) vapor, nitrous oxide (N_2O), nitrogen dioxide (NO_2), nitric oxide (NO), carbon monoxide (CO), and sulfur dioxide (SO_2).[5,9] AFCRL has been funding some work on HNO_3 and NO_2, with which RRI has been cooperating, and the N. P. L. group[47] has been doing laboratory spectroscopy on these species; reduction to line parameters has not yet been accomplished, however, and it is line parameters which are required for SLAM-type computations.[57] Also, as discussed in Ref. 2, as well as in Sec. II below, ongoing work on the oxygen microwave-spectrum[31] line-widths must be incorporated into the line parameters or into the SLAM program if the ±25% uncertainty indicated in Figs. 5 and 6 is to be reduced.[5,9] Direct measurement of the line widths of the oxygen submillimeter lines might further improve not only the submillimeter transmission predictions, but also those in the microwave region.[2] Such measurements have been recommended by us.[2,9]

As to scattering from clouds, the theory seems to be well in hand.[8,38] However, in most of the spectral region under discussion, relative transparency occurs only at altitudes sufficiently high for water clouds to be rare. Thus, scattering from ice clouds (e. g., cirrus) becomes important.[5,8,9] Little is known concerning the complex index of refraction of ice at cirrus temperatures,[5,8] so that RRI has suggested measurements of the complex refractive index.[9] The non-ellipsoidal shape of the ice crystals is also a problem which merits further study.

Owing to time constraints, the SLAM program does not yet have a dispersion-prediction capability. As discussed above, such a capability is relatively easy to implement, and should be done.[5,9] Extension to turbulence-prediction is also possible and desirable.

Another area in which an improvement can be made in the data base needed for system design in the millimeter-to-submillimeter wave region is that of receiver technology.[5] It is clear from the literature survey performed for the present study that data on receivers in this spectral region is available, but scattered widely over the literature. It should be studied systematically.

Finally, as indicated in Section V, RRI has proposed the preparation of specialized bibliographies intended for use by systems designers in the region between 50 GHz and 3 THz on the subjects covered by the over 1000 references studied during the course of the present contract. Owing to the interdisciplinary nature of the subject matter, these references are to be found in the geophysical, spectroscopic, optical engineering, astronomical, and chemical literature, besides the literature which a microwave or communications system engineer is likely to consult. The resulting (apparent) data gap can be bridged by means of such subject bibliographies.

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